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Overview of power inverter topologies and control structures for grid connected photovoltaic systems

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ABSTRACT

In grid-connected photovoltaic systems, a key consideration in the design and operation of inverters is how to achieve high efficiency with power output for different power configurations. The requirements for inverter connection include: maximum power point, high efficiency, control power injected into the grid, and low total harmonic distortion of the currents injected into the grid. Consequently, the performance of the inverters connected to the grid depends largely on the control strategy applied. This paper gives an overview of power inverter topologies and control structures for grid connected photovoltaic systems. In the first section, various configurations for grid connected photovoltaic systems and power inverter topologies are described. The following sections report, investigate and present control structures for single phase and three phase inverters. Some solutions to control the power injected into the grid and functional structures of each configuration are proposed.

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1. Introduction

With the increasing concern about global environmental protection, the need to produce pollution-free natural energy such as solar energy has received great interest as an alternative source of energy for the future since it is clean, pollution-free and inexhaustible.

Over the last decade, PV technology has shown the potential to become a major source of power generation for the world—with robust and continuous growth even during times of financial and economic crisis. That growth is expected to continue in the years ahead as worldwide awareness for the advantages of PV increases. At the end of 2010, the world's PV cumulative installed capacity was approaching 41 GW. One year later it was 71 GW. In 2012, more than 100 GW were installed as shown in Fig. 1. PV is now, after hydro and wind power, the third most important renewable energy source in terms of globally installed capacity. The growth rate of PV during 2012 reached almost 70%, an outstanding level among all renewable technologies [1].

The number of PV installations has an exponential growth, mainly due to the governments and utility companies that support programs which focus on grid-connected PV systems [2].

In an effort to use solar energy effectively, a great deal of research has been done on the grid-connected photovoltaic generation systems. Fig. 2 shows the total PV power installed in the Europe, 98.7% correspond to PV grid-connected and only 1.3% for off grid.

In PV systems connected to the grid, the inverter which converts the output direct current (DC) of the solar modules to the alternate current (AC) is receiving increased interest in order to generate power to utility. Many topologies are used to this purpose. This paper gives an overview of power inverter topologies and control structures for grid connected photovoltaic systems. In the first section, various configurations for grid connected photovoltaic systems and power inverter topologies are described. The following sections report, investigate and present control structures for single phase and three phase inverters. Some solutions to control the power injected into the grid and functional structures of each configuration are proposed.

2. Structure topologies for grid-connected photovoltaic systems

2.1. Central inverters

Central Technology illustrated in Fig. 3(a), was based on centralized inverters that interfaced a large number of PV modules to the grid [2–5]. The PV modules were divided into series connections (called strings), each one generating a sufficiently high voltage to avoid further amplification. These series connections were then connected in parallel, through string diodes, in order to reach high power levels of 10–250 kW [5]. This centralized inverter includes some severe limitations, such as high-voltage DC cables between the PV modules and the inverter, power losses due to a centralized MPPT, mismatch losses between the PV modules, losses in the string diodes, and a non-flexible design where the benefits of mass production could not be reached. The failure of the central inverter results in that the whole PV plant fails to operate. The grid-connected stage was usually line commutated by means of thyristors, involving many current harmonics and poor power quality [6-11].

2.2. String inverters

The string inverters shown in Fig. 3(b), is a reduced version of the centralized inverter, where a single string of PV modules is connected to the inverter [2,3]. The input voltage may be high enough to avoid voltage amplification. There are no losses associated with string diodes and separate Maximum Power Point (MPP) tracking MPPTs can be applied to each string. This increases the energy yield via the reduction of mismatching and partial shading losses. These superior technical characteristics lead to the increase in energy yield and enhance the supply reliability. This increases the overall efficiency compared to the centralized inverter, and reduces the price, due to mass production.

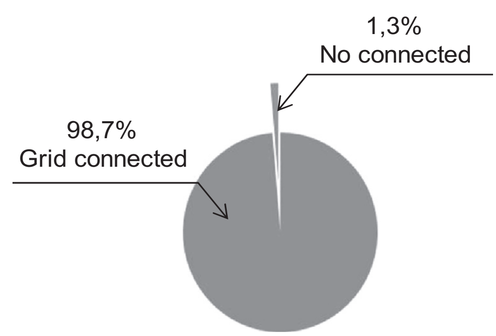
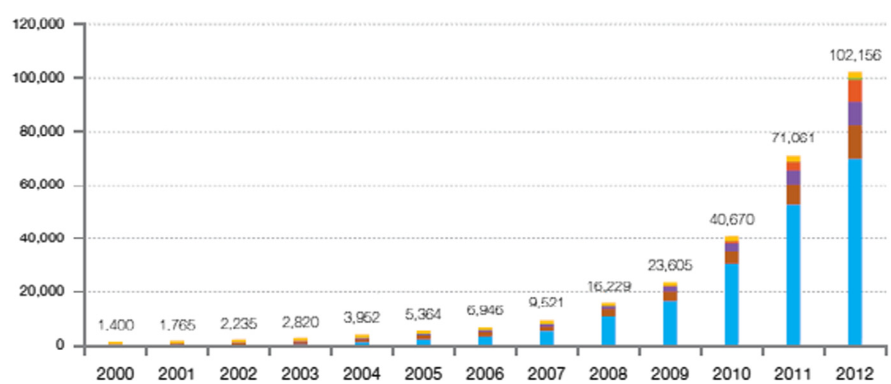


Fig. 2. PV power installed in Europe.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
ROW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	71	192	601
China	19	24	42	52	62	70	80	100	140	300	800	3,300	8,300
Americas	146	178	225	290	394	501	650	863	1,209	1,752	2,780	4,959	8,717
APAC	355	495	686	916	1,198	1,500	1,825	2,096	2,631	3,373	4,956	7,628	12,397
Europe	129	262	396	598	1,305	2,289	3,281	5,310	11,020	16,850	30,472	52,884	70,043
Total	1,400	1,765	2,235	2,820	3,952	5,364	6,946	9,521	16,229	23,605	40,670	71,061	102,156

Fig. 1. PV power in the world [1].

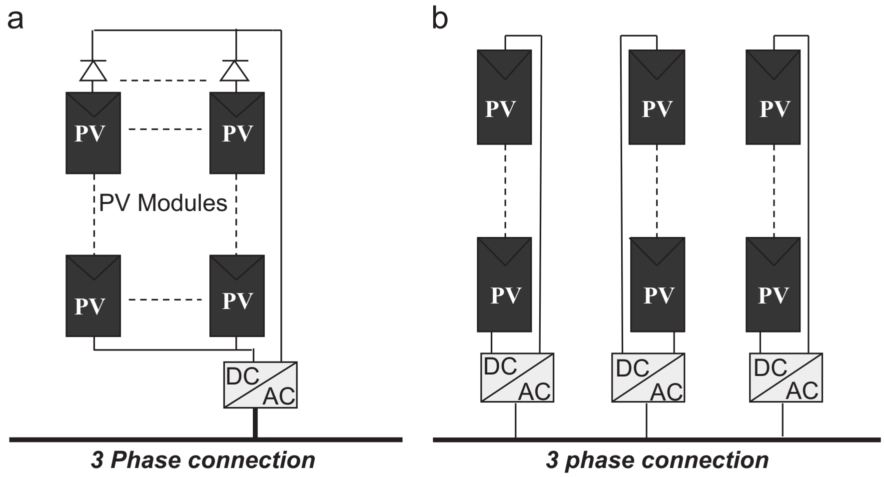


Fig. 3. (a) Centralized technology. (b) String technology.

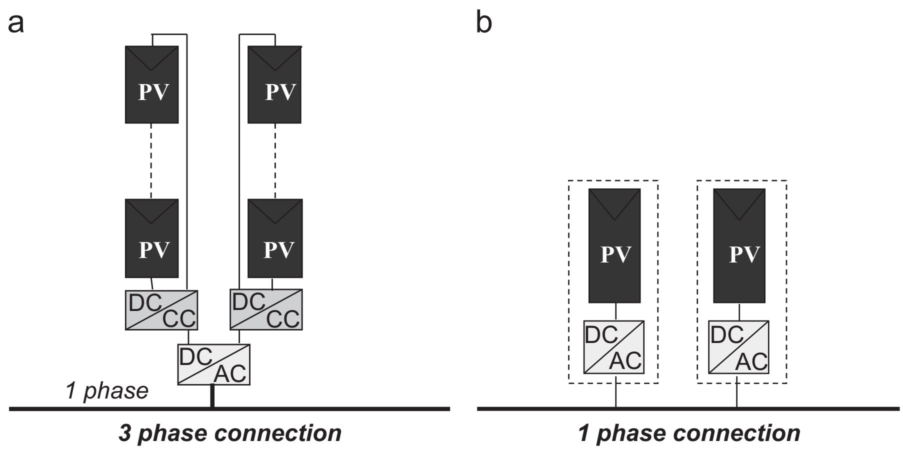


Fig. 4. (a) Multistring technology. (b) AC Module.

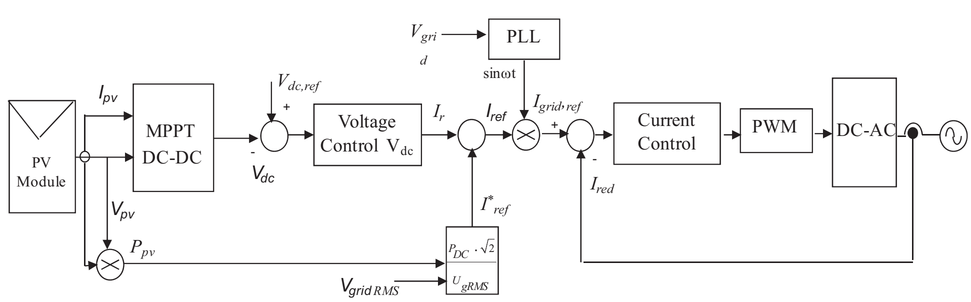


Fig. 5. Control structure topology for single phase with DC–DC converter.

String inverters have evolved as a standard in PV system technology for grid connected PV plants [3,8–11].

2.3. Multi-string inverters

The multi-string inverter depicted in Fig. 4(a) is the further development of the string inverter, where several strings are interfaced with their own DC–DC converter (separate MPP tracking systems) to a common DC–AC inverter [2,3]. This is beneficial, compared to the centralized system, since every string can be controlled individually. Accordingly, a compact and cost-effective solution, which combines the advantages of central and string technologies, is achieved. This multi-string topology allows for the integration of PV strings of different technologies and of various orientations (south, north, west and east). These characteristics allow time-shifted solar power, which optimizes the operation efficiencies of each string separately. The application area of the multi-string inverter covers PV plants of 3–10 kW [5,9,12].

2.4. AC modules

The AC module depicted in Fig. 5(b) is the integration of the inverter and PV module into one electrical device [1]. It removes the mismatch losses between PV modules since there is only one PV module, as well as supports optimal adjustment between the PV module and the inverter and, hence, the individual MPPT. It includes the possibility of a facilitated enlargement of the system, due to the modular structure. The necessary high voltage-amplification may

reduce the overall efficiency and increase the price per watt, because of more complex circuit topologies. The present solutions use self-commutated DC–AC [3,9,13].

3. Impact of inverter configuration on energy cost of grid-connected photovoltaic systems

There are typically three possible inverter scenarios for a PV grid system: single central inverter, multiple string inverters and AC modules. The choice is given mainly by the power of the system. Therefore, AC module is chosen for low power of the system (around 100 W typical). And a single central inverter or multiple string inverters will be chosen depending on the designer. Technically it is possible to use both topologies. Therefore in order to promote large-scale solar power generation, it is necessary to optimize the topologies and the PV system design to make solar energy economically acceptable and attractive. There are many aspects to evaluate a PV system design, such as efficiency, reliability, cost, energy yield. Currently research on solar power and suggested procedures to model and evaluate solar technologies are realized [15-18].

Refs. [19,20] present an overview of the state of technique for PV inverters used in low voltage grid-connected PV systems: Different and important aspects with respect to performance of some PV grid-installation have been analyzed. Ref. [21] studied the impact of inverter configuration on energy yield based on a simple efficiency model. Ref. [22] optimized the selection and configuration of PV modules and inverters based on a generalized PV system model to maximize the net profit. The efficiency and reliability of inverters were not modeled in detail in such a complicated problem. Ref. [23] introduced a reliability model to energy yield estimation to compare central inverters and module integrated inverters. However, they did not take into account environmental conditions and inverter efficiency characteristics. Ref. [24] suggests that energy yield and levelized cost of energy should be estimated considering the PV array scale, environmental conditions, system cost, inverter efficiency and reliability. The efficiency characteristic of parallel inverters with a common DC bus is deliberated along with the optimal operation strategy. Inverter system performance ratio (ISPR) is proposed as an overall index of lifetime energy conversion efficiency. It shows that the configuration with a common DC bus is a potential solution to reduce the energy cost of PV power generation systems. As results, it is found that optimizing the PV panel orientation can improve the probability distribution of solar irradiance on the panel, and it is confirmed that an oversized PV array may help reduce the energy cost.

4. Control structures for grid-connected photovoltaic systems

The DC–AC converters inject sinusoidal current into the grid controlling the power factor. Therefore, the inverter converts the DC power from the PV generator into AC power for grid injection. One important part of the system PV connected to the grid is its control. The control can be divided into two important parts.

(1) MPP controller, with the main property to extract the maximum power from the input source (PV module).
(2) Inverter controller, which ensure the control of active and reactive power generated to the grid; the control of DC-link voltage; high quality of the injected power and grid synchronization.

The control strategy applied to the inverter mainly of two cascaded loops. Usually, there is a fast internal current loop, which regulates the grid current, and an external voltage loop, which controls the DC-link voltage. The current loop is responsible for power quality issues and current protection; thus, harmonic compensation and dynamics are the important properties of the current controller. The DC-link voltage controller is designed for balancing the power flow in the system. Usually, the design of this external controller aims the optimal regulation and stability of systems having slow dynamics. This voltage loop is designed for a stability time higher than the internal current loop by 5 to 20 times. The internal and external loops can be considered decoupling, therefore the transfer function of the current control loop is not considered when the voltage controller is designed [25–33].

In some works, the control of the inverter connected to the grid is based on a DC-link voltage loop cascaded with an inner power loop instead of a current one. In this way, the current injected into the grid is indirectly controlled.

4.1. Control structure for single phase with DC–DC converter

The control structure for the single phase with the DC–DC converter proposed in [5,29], is shown in Fig. 5. The most common control structure for the DC–AC grid converter is a current-controlled H-bridge PWM inverter having low-pass output filters. Typically L filters are used but the new trend is to use LCL filters that have a higher order, which leads to more compact designs:

- Control of instantaneous values current
- Current is injected in phase with the grid voltage (PF=1)
- Use PLL for synchronization of the current I_{grid} and V_{grid}

4.1.1. MPPT control

In order to capture the maximum power, a maximum power point tracker (MPPT) is required. The maximum power point of PV panels is a function of solar irradiance and temperature as depicted in Fig. 6. This function can be implemented either in the DC–DC converter or in the DC–AC converter. Several algorithms can be used in order to implement the MPPT [37-39]: perturb and observe, incremental conductance, parasitic capacitance and constant voltage, but only the first two are the most frequently used. The incremental conductance algorithm has advantages compared to perturb and observe as it can determine when the MPPT has reached the MPP, where perturb and observe oscillates around the MPP. Also, incremental conductance can rapidly track the increase and decrease of irradiance conditions with higher accuracy than perturb and observe.

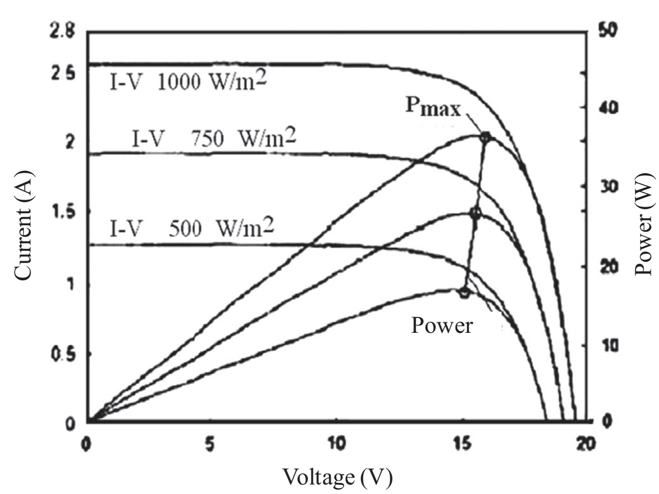


Fig. 6. I.V PV characteristic.

4.1.2. DC–DC boost converter control

In order to control the output DC-voltage to a desired value, a control system which can automatically adjust the duty cycle is needed.

- *Inverter control*: In Fig. 5, the variable control of a control structure for a PV system connected to the grid is shown. This control is divided into 2 control loops, the internal current control loop and the external DC-bus voltage control loop.
- The internal control loop is used to control the instantaneous values of AC current in order to generate a sinusoidal current in phase with the grid voltage. The reference current $I_{\rm ref}$, is generated from a PLL sinusoidal signal reference which synchronizes the output inverter current with grid voltage as shown in Fig. 5 [29]. The amplitude current is regulated from the external voltage loop.
- The external loop, ensures the regulation of DC-bus voltage $V_{\rm DC}$. It's necessary to limit the $V_{\rm DC}$ voltage, however, the control of $V_{\rm DC}$ guarantees the regulation of power injected into the grid.
- In [25], a control structure for topology with DC/DC converter and L filter is presented (Fig. 7). In this case, the reference current $I_{\rm ref}$, is generated from the sinusoidal signal reference determinate from a grid voltage sample.

This structure is associated with proportional integral controllers (PI). To improve the performance of the PI controller in such a current control structure and to cancel the voltage ripples of the photovoltaic generator, due to variations in the instantaneous power flow through the photovoltaic system, will depend on the change of atmospheric conditions (mainly the irradiance and temperature), the faster response of the boost control loop, the inverter and the value of the DC bus capacitor. On the other hand, the output voltage (the mains voltage) represents an external disturbance of considerable magnitude at 50 Hz for the system. There exists a compensation of these effects at the output of the PI controller so as to calculate directly the reference voltage for the inductance [25]. Fig. 9 shows the control loop of the inverter output current.

The inverter output current expression is given:

$$I_{out}(s) = \frac{D \times V_{GPV}(s) - V_{out}(s)}{Ls} \tag{1}$$

The feed-forward technique [25] is based on including new terms to variables control, in this case the duty cycle, in order to eliminate the dependence related to the perturbations of control system.

To compensate the effect of output voltage, the average and filtered output voltage values, called $v_{\rm out,mes}$, are used Fig. 8. However, to compensate the voltage $v_{\rm Gpv}$, it's necessary to use, the measured value before filtered.

In this case, it is necessary to calculate a duty cycle since the transfers' functions:

$$d = \frac{v_{L,ref} + v_{out,mes}}{v_{GPV,mes}} \tag{2}$$

K_{sv} the same step of measured circuits, obtained:

$$d = \frac{v_{L,ref} + K_{sv} v_{out}}{K_{sv} v_{GPV}} \tag{3}$$

From the duty cycle, the inductance voltage V_L can be deduced:

$$v_L = d v_{GPV} - v_{out} = \frac{v_{L,ref}}{K_{sv}} \tag{4}$$

The advantage of this control structure is the control of the instantaneous power injected into the grid from the solar module and the synchronization of the current signal with the grid voltage (voltage and current in phase) which guarantee a higher power factor and improve the MPPT dynamic. The disadvantage is the noise in the inverter output current signal due to the use of the grid signal sample for generating and synchronizing the reference current with the grid signal.

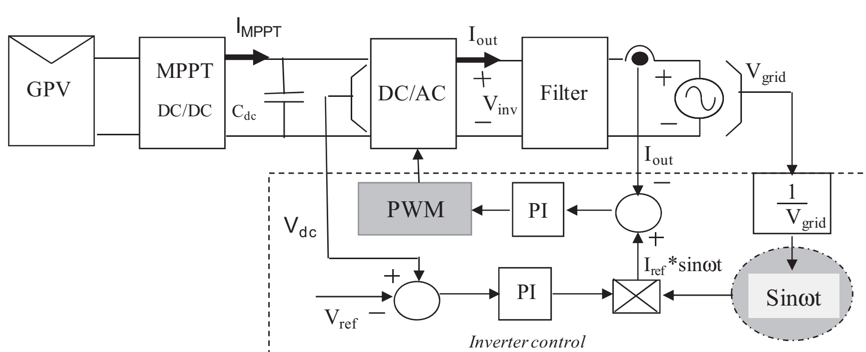


Fig. 7. Control structure with DC–DC converter and L Filter.

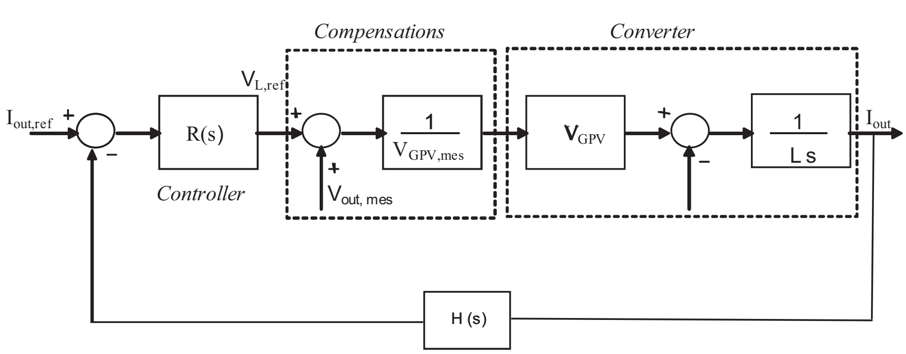


Fig. 8. Control loop structure of alternative output current.

[29,30], propose a control structure for topologies with DC–DC converter and LCL filter, Fig. 9. This structure has the following characteristics:

- Typical structure for powers 5 kW max.
- PI controller (Proportional Integral) or PR (Proportional Resonant) for current control.
- PWM control, hysteresis or predictive.
- PI controller for voltage control.
- Optional transformer.

The principal elements of this control structure are, the algorithm control based on the PLL, the MPPT and the control of the provided power and injected current into the grid.

4.2. Control structure for single phase without DC–DC converter

In Fig. 10, the control structure for single phase without DC–DC converter that is proposed in [5]. The same control loop, the internal current one and the external voltage loop [7].

The difference with respect to the control structure for topologies with DC–DC converter, the DC–AC inverter determines the maximum power point.

Another control structure proposed and shown in [29], is the power control based on the lineal current control injected into the grid. The power control structure for the PV system connected to the grid is in the range of 1–5 kW.

The full bridge inverter connected to the grid across the LCL filter is shown in Fig. 11.

This power control structure is divided principally on the synchronize algorithm based on the *Phase Locked Loop* (PLL), a maximum power point (MPPT), the input power control of the continuous side and the injected current control into the grid.

- *PLL*: used for the synchronization of the inverter output current with the grid voltage, the power factor equal to the unity, also allowing for the generation of the sinusoidal and clean reference signal [30,41–43].
- *Input power control*: In this case, the control strategy for power configuration of PV system uses a feed-forward and does not include the DC/DC converter is presented in Fig. 12.
  The amplitude value of the reference current is calculated from the solar modules power P_{pv} and the RMS voltage grid ($V_{grid,RMS}$), adding the controller value (I_r) of the output continued DC bus V_{DC}. The result is expressed with the amplitude reference (I_{ref}) as shown in Fig. 12 [29].
  The use of the feed-forward improves the dynamic response of the PV system. The DC-bus voltage controller ensures a fast PV system response to the input power change [25,29].
- *Current control*: the PI controller is used with the feed-forward technique of the grid voltage as shown in Fig. 13.

The transfer function of the PI controller, $G_{PI}(s)$ is defined as:

$$G_{PI} = K_p + \frac{K_I}{s} \tag{5}$$

As mentioned previously, the feed-forward technique improves the dynamic response. This guarantees the stability of perturbations in the system introduced by the feedback voltage [5,6,29,30] and proposes an alternative solution for the poor performances of the PI controller, which includes the use of the proportional resonant controller PR. The current loop of the PV inverter with the PR controller is presented in Fig. 14.

The transfer function of the PR current controller is defined in [6,31,32,49].

$$G_c(s) = K_p + K_I \frac{s}{s^2 + \omega_0^2} \tag{6}$$

The transfer function $G_h(s)$ of the harmonic compensator (HC) defined as [5].

$$G_h(s) = \sum_{h=3,5,7} K_{Ih} \frac{s}{s^2 + (\omega_0 h)^2} \tag{7}$$

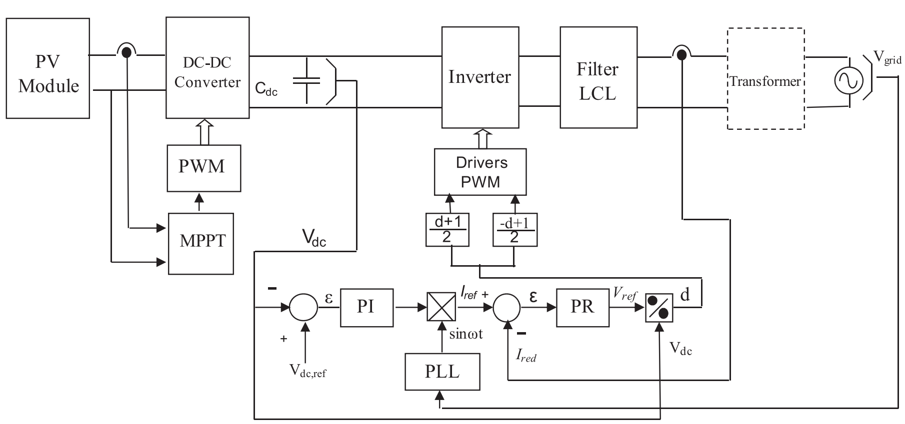


Fig. 9. Control structure with DC–DC converter and LCL filter.

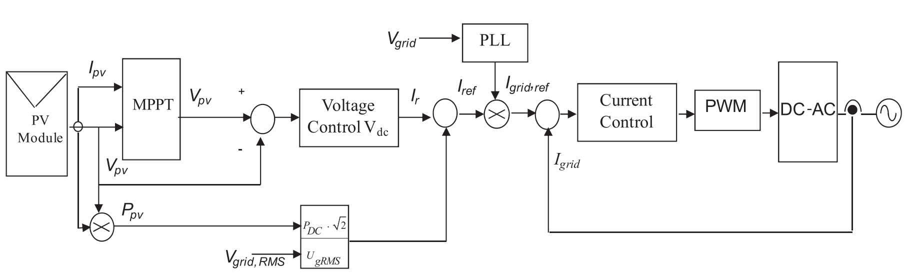


Fig. 10. Control structure for single phase without DC–DC converter.

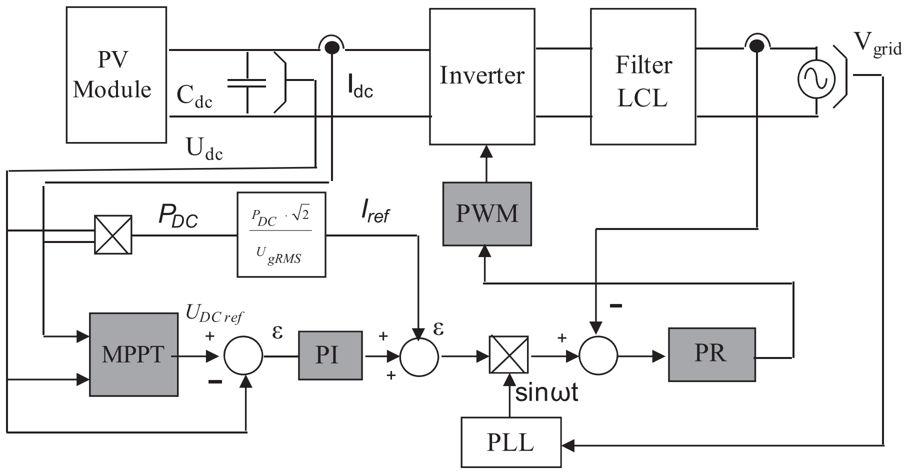


Fig. 11. Injected power control structure.

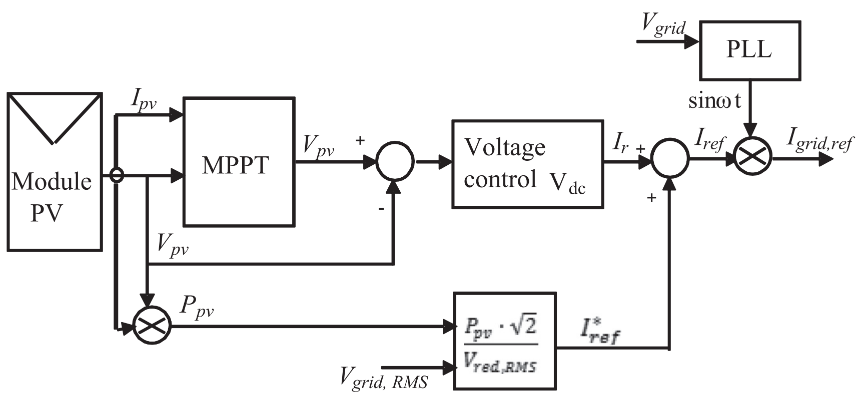


Fig. 12. Control structure of input power (Solar panel power).

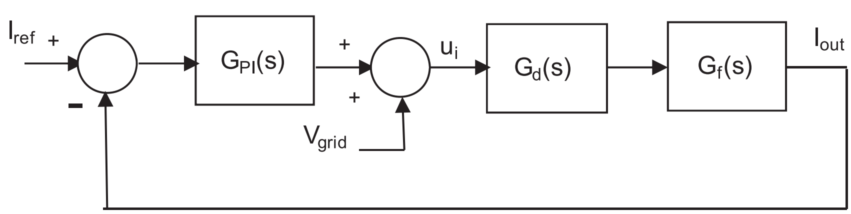


Fig. 13. Inverter current loop with PI controller.

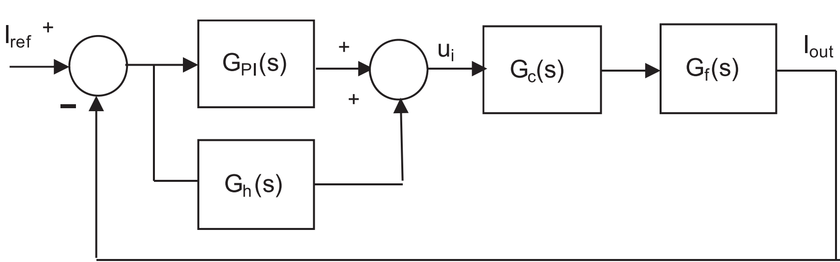


Fig. 14. Inverter current loop with PR controller.

The compensator HC is designed to compensate for the 3rd, 5th and 7th selected harmonics as they are the most predominant ones in the current spectrum.

In this case it has been shown that the use of the PR+HC controller gives a better dynamic response of the system, very low harmonic distortion (0.5%) and eliminates the error in the steady state without using the feed-forward voltage. Adding the harmonic compensator (HC) to the resonant proportional controller (PR) makes the system more reliable with better elimination of harmonics.

5. Reactive power requirements

Power factor control and reactive power regulation is known as the most important issue in connecting PV array to the grid. The grid-connected inverter must be controlled in such a way that not only it injects a current with low total harmonic distortion (THD), but also allows controlling the injected reactive power into the grid selecting a proper power factor according to the grid demands: active or reactive power. Thus, the most efficient systems are those that allow varying

the power injected into the grid, both active and reactive, depending on the power grid needs [35,36,50].

Some solutions are proposed [2,13,14,34], in order to obtain the high reliability inverter and many control techniques of grid-connected PV inverter have been proposed in literature. A multiple closed loops control structure for grid current and DC link voltage are given in [44-46,51,52]. Other control structures consist of using a classical PI and/or bang–bang Controllers [53,54]. Other authors propose the use of phase lock loop (PLL) control of the grid current [55–57]. An extended Direct Power Control (EDPC), based on geometrical considerations about inverter voltage vectors and their in fluencies on active and reactive power change, is proposed in [58].

The input output Feedback Linearization Control (FLC) technique widely applied on electrical motors control [59] and PWM rectifier's control [60] has been applied on PV inverters by Ref. [61], but it gives a complex model of the inverter, including switching functions. In [62], the power factor of a grid-connected photovoltaic inverter is controlled using the input output Feedback Linearization Control (FLC) technique. This technique transforms the nonlinear state model of the inverter in the d-q reference frame into two equivalent linear subsystems, in order to separately control the grid power factor and the DC link voltage of the inverter. This method allows control of both power factor and DC link voltage using the same control algorithm. Also, in this control method, the MPP control is moved towards the DC–AC converter, hence, there is no need to use a DC–DC converter, which increases the simplicity of the conversion system. Compared to other control methods, in [63,64], the grid power factor is controlled using a previously calculated and tabulated PWM, and acting on the phase shift between grid voltage and inverter output voltage as a control parameter, The proposed control strategy is capable to control, not only the current injected into the grid, but also the power factor, with a minimum number of DSPWM (Digital Sinusoidal Pulse Width Modulation) patterns. Varying the power factor, within a certain range, the injected reactive power (inductive or capacitive) can be dynamically changed and controlled, in order to obtain the high reliability of the inverter. This method break the limitations of existing grid-connected system where the inverter topology is designed to supply only active power to the grid without injecting reactive power.

6. Control based on the shifting phase for grid connected photovoltaic inverter

In [63,64], the proposed control structure, for a PWM single-phase inverter connected to the grid, is shown in Fig. 15. The photovoltaic system consists in a photovoltaic generator (PVG), a maximum power point tracking (MPPT) block and a PWM single phase inverter (DC/AC).

The DC/DC converter is employed to boost the PV-array voltage to an appropriate level based on the magnitude of utility voltage, while the controller of the DC–DC converter is designed to operate as a maximum power point (MPP) that increases the economic feasibility of the PV system. Several algorithms can be used in order to implement the MPPT [38,39]: perturb and observe, incremental conductance, parasitic capacitance and constant voltage, but only the first two are the most frequently used.

For the MPPT controller, the perturb-and-observe method is adopted owing to its simple structure and the fact that it requires fewer measured parameters. This strategy is implemented to operate under rapidly changing solar radiation in a power PV grid connected system, using only one variable: PV output current. The constant voltage method is accomplished by keeping the voltage in the PV terminals constant and close to the MPP.

The control loop for the PWM inverter is assured by the output current control, the DC bus control and synchronizing to the grid, to inject power into the grid at all time. In this case the voltage at the Point of Common Coupling (PCC; the point where the load would be connected in parallel to the two sources), is not considering. The inverter is decoupled of the grid. The output voltage of the PWM inverter is already set by the utility PV modules. Therefore the inverter is current controlled to ensure only power injection into the grid.

The power control is obtained by means of the inverter output voltage shifting phase, PCSP (*Power Control Shifting Phase*). In Fig. 15 are represented a controller with two control loops: an inner one, that allows controlling the inverter output current and an outer one to control the DC bus V_{DC}.

The reference of the output current (I_{ref}) depends on the DC bus voltage (V_{DC}) and its reference (V_{ref}). A low pass Filter is incorporate in order to ensure that high frequency switching noise present in the measured inverter output current signal does not pass through to the PI controller.

The control structure is associated with proportional–integral (PI) controllers since they have a satisfactory behavior when regulating DC variables.

In this case the output current I_{out} is not controlled varying the amplitude modulation index m_a, since it is considered constant, but by phase shifting the inverter output voltage with respect to the grid voltage. The adequate value of the phase shifting is obtained taking into account the zero crossing detector (ZCD) of the reference ($V_{grid,ref}$). The DSPWM generates the driving signals for the PWM inverter according to the switching pattern, with the corresponding phase shifting, in order to satisfy the current reference, I_{ref}. So the power factor is indirectly controlled. As a result, a certain amount of reactive power can be generated.

The main advantage of this control strategy is its simplicity with respect to the computational requirements of the control circuit and hardware implementation. On the other hand, it allows reconfiguring the control in a fast and simple way in case that not only an active power needs to be injected but also a reactive one.

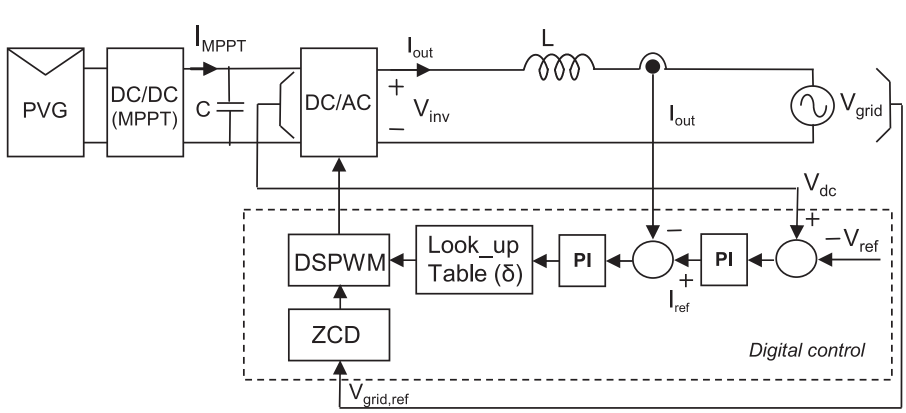


Fig. 15. Control structure based on the shifting phase for a single phase connected to the grid.

Table 1, resume the advantage and inconvenient of each control structures for single phase topologies.

7. Control structure for three-phase inverter connected to the grid

To study stationary and dynamic regimes in three-phase systems, the application of "vector control" (Parck vector) is a powerful tool for the analysis and control of DC–AC converters, enabling abstraction of differential equations that govern the behavior of the three-phase system in independent rotating shafts. The main disadvantage of using this control method is that it introduces a nonlinear part, a rotation of axes (mathematical transformations), which requires a lot of computing power, an issue that is solved with existing microcontrollers and DSP.

7.1. dq control

The concept of decoupled active and reactive power control of three-phase inverter is realized in the synchronous reference frame or also called *dq* control by using the *abc-dq* transformation for converting the grid current and voltages into a rotating reference system with the grid voltage, these variable control values are transformed into continuous. In this way, the ac current is decoupled into active and reactive power components, Id and Iq, respectively. These current components are then regulated in order to eliminate the error between the reference and measured values of the active and reactive powers. In most cases, the active power current component, Id, is regulated through a DC-link voltage control aiming at balancing the active power flow in the system [47,48,65]. As shown in Fig. 16, the power control loop is followed by a current control system. By comparing the reference and measured currents, the current controller should generate the proper switching states for the inverter to eliminate the current error and produce the desired ac current waveform [66,67]. A schematic of the *dq* control is presented in Fig. 16. In the case that the reactive power has to be controlled, a reactive power reference must be imposed to the system. Linear PI controller is an established reference tracking technique associated with the d-q control structure due their satisfactory combinational performance. Eq. (8) states the transfer function on the d-q coordinate structure.

$$G_{PI}^{dq}(s) = \begin{pmatrix} K_p + \frac{K_I}{s} & 0 \\ 0 & K_p + \frac{K_I}{s} \end{pmatrix} \quad (8)$$

where K_p is the proportional gain and K_i is the integral gain of the controller.

For improving the performance of PI controller in such a structure, as depicted in Fig. 16, cross-coupling terms and voltage feed forward are usually used [31–33]. In any case, with all these improvements, the compensation capability of the low-order harmonics in the case of PI controllers is very poor. [5–7,18] proposes the use of PR+HC controller to improve the system dynamic response, harmonic distortion, eliminate steady state error and prevent the use of the feed-forward. The phase-locked loop (PLL) technique [29,30] is usually used in extracting the phase angle of the grid voltages in the case of PV systems.

7.2. αβ–Control

In this case, the grid currents are transformed into a stationary reference frame using the $abc \rightarrow \alpha\beta$ module [33,40], as shown in Fig. 16. The *abc* control is to have an individual controller for each grid current; characteristic to this controller is the fact that it achieves a very high gain around the resonance frequency, thus being capable of eliminating the steady-state error between the controlled signal and its reference. High dynamic characteristics of the Proportional Resonant Controller PR controller have been reported in different works, and which is gaining common popularity in the current control for networked systems, is an

Table 1
Advantage and inconvenient of control structures for single phase inverters.

Topologies	Advantage	Inconvenient
Single phase inverter with DC/DC converter	• Instantaneous current control • Fast Dynamic	• No full control of power factor • Complex Hardware circuit
Single phase inverter without DC/DC converter	• Instantaneous current control • Simplicity of the conversion system • Fast Dynamic	• No full control of power factor • Complex Hardware circuit
Single phase inverter with PCSP	• Simplicity • Less circuitry • Few resources • Reactive power controlled	• No full control of current • No fast dynamics

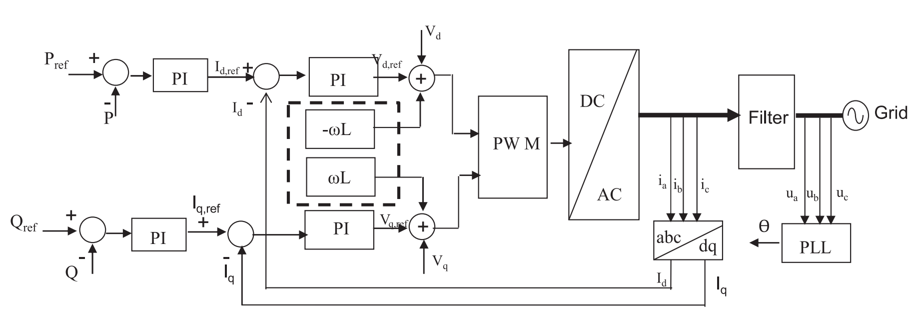


Fig. 16. General structure for *dq* control strategy.

alternative solution for performance under the proportional integral PI controller. The basic operation of the controller PR, is based on the introduction of an infinite gain at the resonant frequency to eliminate the steady state error at this frequency between the control signal and the reference. It does not require the use of feed forward [7,21].The transfer matrix of the PR controller in the stationary reference frame is given by:

$$G_{PR}^{\alpha\beta}(s) = \begin{pmatrix} K_p + \frac{K_I}{s^2+\omega^2} & 0 \\ 0 & K_p + \frac{K_I}{s^2+\omega^2} \end{pmatrix} \tag{9}$$

7.3. abc control

As mentioned in [33], in *abc* control an individual controller for each grid current is used however, in any case, having three independent controllers is possible by having extra considerations in the controller design. *abc* control is a structure where nonlinear controllers like hysteresis or dead beat are preferred due to their high dynamics. The performance of these controllers is proportional to the sampling frequency; hence, the rapid development of digital systems such as digital signal processors or field-programmable gate array is an advantage for such an implementation. A possible implementation of *abc* control is depicted in Fig. 17 [33], where the output of DC-link voltage controller sets the active current reference. Using the phase angle of the grid voltages provided by a PLL system, the three current references are created. Each of them is compared with the corresponding measured current, and the error goes into the controller. If hysteresis or dead-beat controllers are employed in the current loop, the modulator is not necessary. The output of these controllers is the switching states for the switches in the power converter. In the case that three PI or PR controllers are used, the modulator is necessary to create the duty cycles for the PWM pattern.

The PI controller is widely used in conjunction with the *dq* control, but its implementation in the *abc* frame is also possible as described in [32].

The implementation of PR controller in *abc* is simple since the controller is already in a stationary frame and the implementation of three controllers is possible as expressed in Eq. (10)

$$G_{PR}^{abc}(s) = \begin{pmatrix} K_p + \frac{K_I}{s^2+\omega^2} & 0 & 0 \\ 0 & K_p + \frac{K_I}{s^2+\omega^2} & 0 \\ 0 & 0 & K_p + \frac{K_I}{s^2+\omega^2} \end{pmatrix} \tag{10}$$

Table 2, resume the advantage and inconvenient of control structures in three phase inverter

8. Conclusion

This paper has presented different topologies of power inverter for grid connected photovoltaic systems. Centralized inverters interface a large number of PV modules to the grid. This included many shortcomings due to the emergence of string inverters, where each single string of PV modules is connected to the DC–AC inverter. The multi-string inverter is the development of the string inverter, where several strings are interfaced with their individual DC–DC converter (separate) MPPT tracking systems) to a common DC–AC inverter. Another trend seen is the development

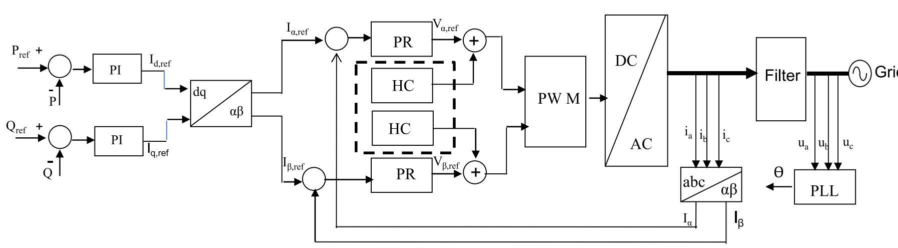


Fig. 17. General structure for $\alpha\beta$ control strategy.

Table 2
Advantage and inconvenient of control structures for three phase inverters.

Control strategies	Associated controller type	Advantage	Inconvenient
dq control	• PI	• Filtering and controlling can be easier achieved • Simplicity	• Very poor compensation capability of the low-order harmonics • The steady-state error is not eliminated
$\alpha\beta$-control	• PR	• Very high gain around the resonance frequency is achieved • The steady-state error is eliminated • High dynamic	• No full control of power factor • Complex Hardware circuit
abc control	• PI		• The transfer function is complex
	• PR	• The transfer function is simple	• More complex than hysteresis and Dead beat
	• Hysteresis	• High dynamic. • Rapid development	• High complexity of the control for current regulation.
	• Dead-Beat	• Simple control for current regulation. • High dynamic. • Rapid development	• Implementation in high frequency micro controller

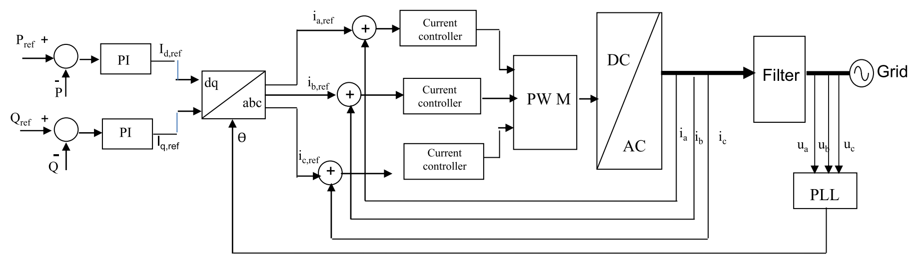


Fig. 18. General structure for *abc* control strategy.

of the ac module, where each PV module is interfaced to the grid with its own DC–AC inverter.

The efficiency characteristic of parallel inverters with a common DC bus is deliberated along with the optimal operation strategy. Inverter system performance ratio (ISPR) is proposed as an overall index of lifetime energy conversion efficiency. It shows that the configuration with a common DC bus is a potential solution to reduce the energy cost of PV power generation systems

A discussion of the different controllers and their ability to compensate for low-order harmonics presented in the grid was given. The PR+HC controller gives a better dynamic response of the system, very low harmonic distortion and eliminates the error in the steady state without using the feed-forward voltage. Adding the harmonic compensator (HC) to the resonant proportional controller (PR) makes the system more reliable with better elimination of harmonics. (Fig. 18).

Power factor control and reactive power regulation is known as the most important issue in connecting PV array to the grid, the control based on the Shifting Phase for Grid Connected Photovoltaic Inverter allows the control in a fast and simple way in case that not only an active power needs to be injected but also a reactive one.

Some Implementation structures for three phase inverters, like *dq*, $\alpha\beta$ and *abc* control were reported. The PI controller is widely used in conjunction with the *dq* control. The implementation of PR controller in $\alpha\beta$ is commonly used. In the *abc* control, nonlinear controllers like hysteresis or dead beat are preferred due to their high dynamics.

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